FSA Engineering & Reliability Development Methods — Can They be Applied Today?

Dr. R.G. Ross, Jr.

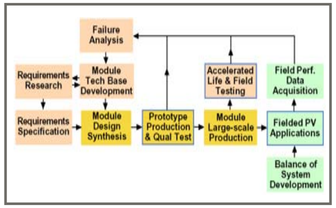
FSA Engineering and Reliability Mngr, 1975-1990

July 11, 2012

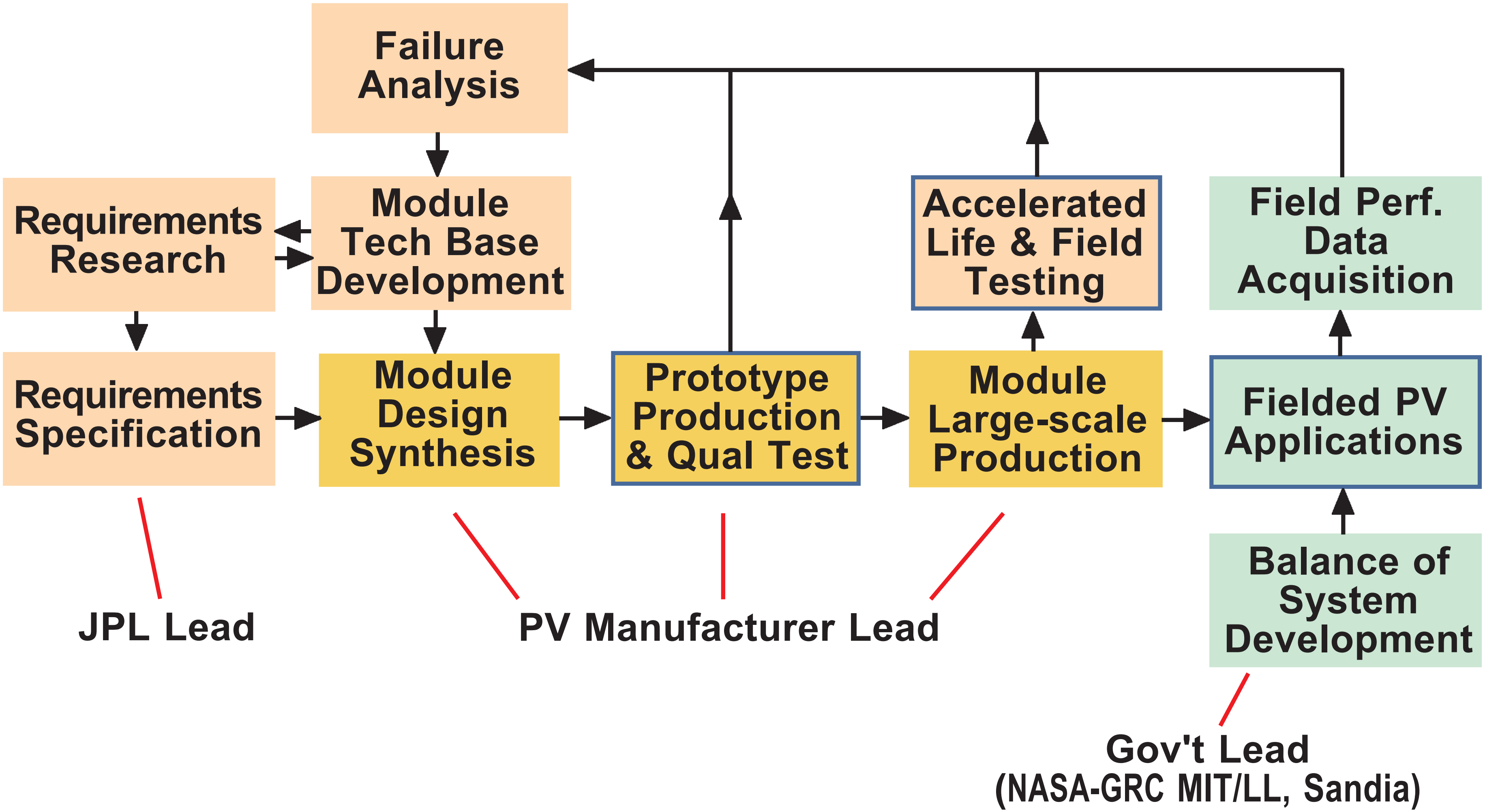
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Topics

- **Formation of an FSA Program Approach**
  - DOE players and roles
  - Closed-loop module development process
  - Provided a forum for rapid communication
- **Requirements Generation for a Future Market**
  - Researching applications and environments
  - Defining initial screening tests
  - Developing safety design standards
- **Resolving Engineering Challenges**
  - Module encapsulant materials development
  - Module circuit and structural design
  - Obtaining feedback from operational systems
- **Achieving Low Cost and Long Life**
  - Understanding degradation mechanisms
  - Developing life-prediction test methods
  - Developing long-life module designs
- **Summary Observations**



DoE / FSA Program Approach to PV Module Development



1975-1985 PV Module R&D Development Process

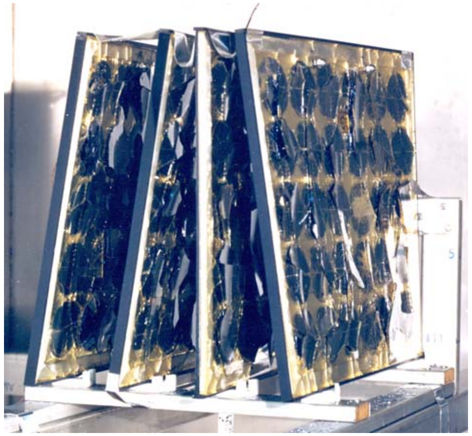
- ✷ Establish detailed generic module requirements for target applications including system operational interfaces, environmental and operational stress levels, reliability, and life
- ✪ Develop preliminary design able to meet requirements
  - Analyze and Test prototype hardware
  - Resolve or design-out requirement shortfalls
- ✪ Fabricate Qual Test samples
- ✪ Conduct full set of Qualification Screening Tests
- ✪ Fabricate & Deliver Large Quantity of Production Modules
- ✷ Conduct Multi-year System-level Functional Field Tests
- ✷ Analyze performance and determine principal failure modes and failure-mechanism parameter dependencies
  - Conduct Reliability Physics Analyses
  - Conduct mechanism-specific Characterization and Life Tests of sample hardware
- ✷ Feed back results into next-generation hardware and Module Specification

✷ = Performed by Nat'l Labs; ✪ = Performed by Module developer

Qualification Testing Objectives and Attributes

OBJECTIVE

- To rapidly and economically screen module designs for prominent (non-wearout) failure mechanisms
- To rapidly assess the relative durability of alternative designs



ADVANTAGES

- Quick turnaround — relatively inexpensive
- Relatively standard procedures allows inter-comparison with historical data
- Separate tests for important environmental and operational stresses aids identification of high-risk mechanisms

LIMITATIONS

- Minimal life-prediction capability (a relative measure of robustness, generally does not quantify life attributes)
- Requires multiple tests and specialized facilities to address the total spectrum of stressing environments
- Number of specimens insufficient to quantify random failures

Full-Up System-Level Testing Objectives and Attributes

OBJECTIVE

- To accurately assess hardware functionality and reliability with special emphasis on system synergisms, interactions, and interfaces

ADVANTAGES

- Complete system interfaces and operating conditions provides reliable assessment of subsystem compatibility issues and degradation mechanisms associated with system interactions or operational stresses
- Inclusion of balance-of-system (BOS) hardware provides data and confidence in complete functional system

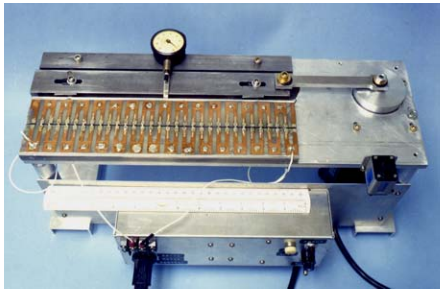
LIMITATIONS

- Requires complete system with all important balance-of-system components and interfaces
- Occurs very late in the design cycle; changes at this point are difficult and expensive
- Added complexity in constructing and testing complete system

Characterization and Accelerated Life Testing Objectives and Attributes

OBJECTIVE

- To understand and quantify the fundamental interdependencies between performance (failure level), environmental and operational stress level, hardware materials and construction features, and time



Cell Interconnect Fatigue Tester

ADVANTAGES

- Mechanism-level understanding achieved by selecting specialized tests and facilities targeted at specific degradation stress environments and construction material parameters
- Carefully controlled parameters (generally at parametric levels) with acceleration consistent with accurate extrapolation to use conditions

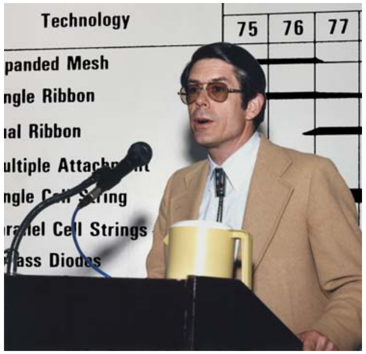
LIMITATIONS

- Expensive and time consuming — requires specialized testing equipment and modestly long test durations (2 weeks to 5 years)
- Requires multiple tests to address the total spectrum of degradation mechanisms and levels
- Number of specimens insufficient to quantify random failures

FSA Used Rapid and Thorough Communication of Development Results

OBJECTIVE

- Rapidly transfer research results to the entire audience of PV researchers and developers (all Industries, academia, and program management); i.e. have everyone rapidly build on successes achieved and quickly learn from any setbacks or deadends.



APPROACH USED

- Conducted Project Integration Meetings (PIMs) every three months with all parties attending and presenting — very much like technical conference, but not open to the public. In addition, had National Program meetings, and International Program meetings and plant/ research facility tours. All results documented in public documents.

OBSERVATIONS

- Required openness and a high degree of collaboration — which was achieved. Quite unique!
- Had many attributes of peer reviewed proposals
- Total FSA Project involved 131 different industrial and academic contractors, and continued on for 10 years

First Task: Examine Performance of the 1975 Modules & Applications

Assessed state of terrestrial PV in 1975

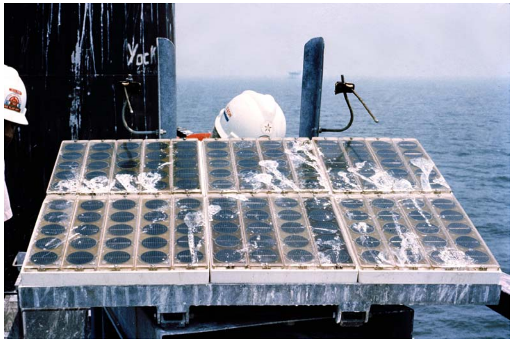
- Coast Guard buoys in Groton, CN
- Oil platforms in the Gulf
- Small remote communication apps

Lessons Learned

- Modules soiled and delaminating
- Wiring, Balance of System (BOS), and maintenance were a real problem

Actions

- Initiated Qual tests to screen out early module failures
- Initiated operating temperature & soiling studies
- Initiated (Block I) procurements of 1975 off-the-shelf modules for extensive testing in larger applications



Developed Requirements for Future PV Markets

System Interfaces and Operational Stresses

- Initiated PV system and array design contracts (GE, Bechtel, Burt Hill Kosar Rittelmann)
- Identified system voltage levels, mounting configurations, applicable codes and missing codes for Utility and Residential applications

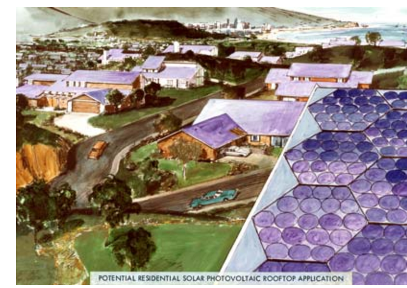
Detailed Environmental Stresses

- Solar and UV exposure across US
- Predicted operating temperatures
- Hail and Wind loading environments
- Solar variability (loss-of-sun statistics)
- Module electrical measurement standards

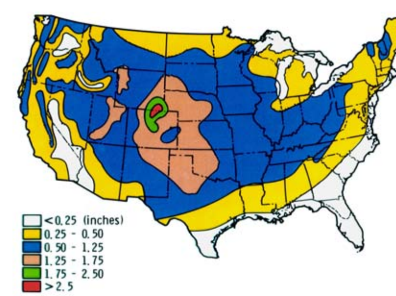
Actions

- Initiated safety codes development at UL which led to UL 1703 and National Electrical Code 690
- Developed testing methods and standards for hail, wind loading, and flammability

Central Station

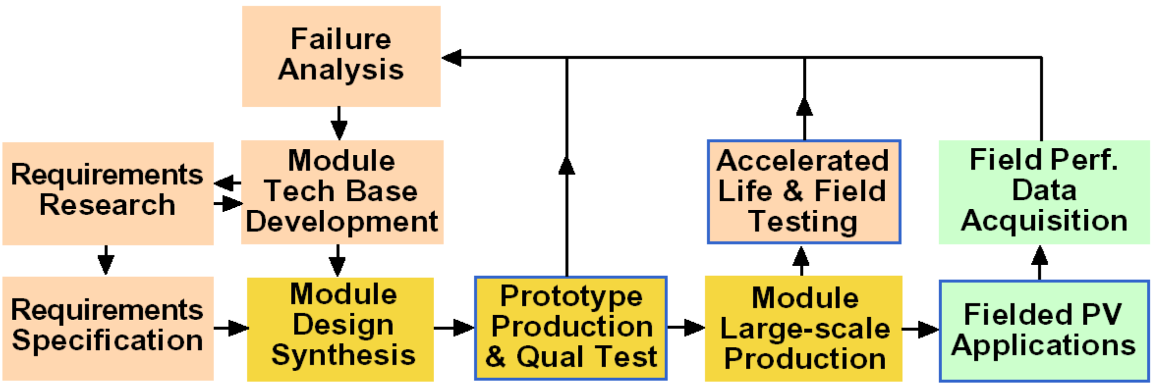


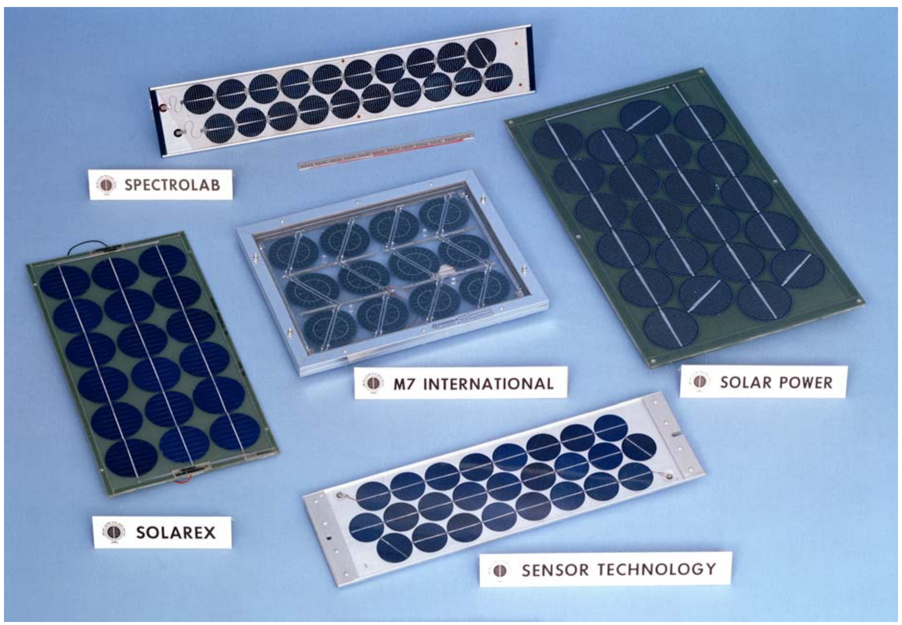
Residential Arrays



Hail Probability

Initial 1975 Block I Modules Were Quite Immature





- Off-the-shelf 1975 designs
- Silicone rubber encapsulant
- G-10 or Alum Rear substrate
- Single cell string
- Single interconnect between cells
- Single solder attachment to cells
- No bypass diodes

Focused on Feedback from First Large Fielded Applications

System Interface and Operational Stresses

- High voltage arcing at broken interconnects
- Hot-spot heating from broken and shadowed cells (1 to 2% cracked cells in field)

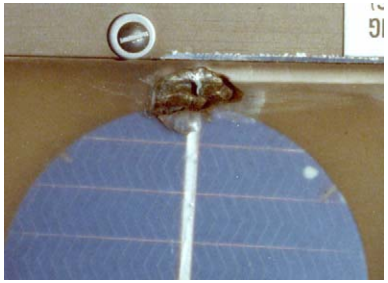
Environment Induced Failures

- High levels of soiling
- Broken cells due to hail impact
- Broken cells due to differential CTE
- Interconnect fatigue due to differential CTE

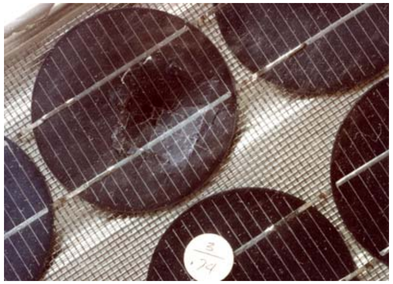
Actions

- Initiate research on alternate encapsulant systems (PVB, EVA, glass, metal, Tedlar)
- Initiate research on arcing, soiling, hail resistance, hot-spot heating, and circuit design strategies for improved reliability

Mead Nebraska test site



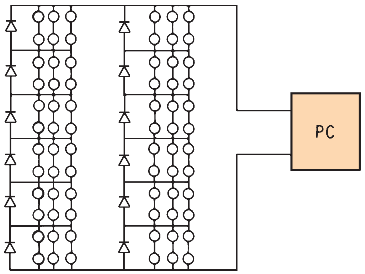
Module Arcing



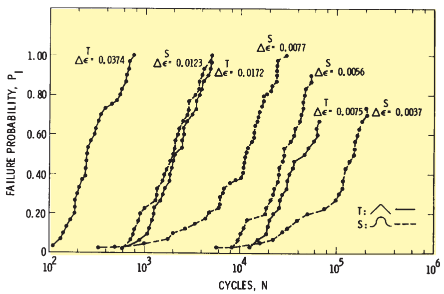
Hail Damage

Focus: Develop Technology Base for Encapsulation and Module Design

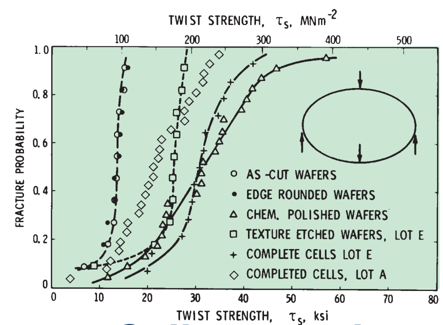
- **New lamination adhesives**, primers, and stabilizers (PVB, EVA, EMA) for lower cost and improved weathering
- **Circuit redundancy configurations** for controlling impact of infrequent cell cracking and broken interconnects
- **Interconnect design methods** to avoid fatigue
- **Cell attachment techniques** to minimize losses due to cell cracking
- **Glass strength** calculation methods
- **Bypass diode design** and hotspot test methods
- **Hail resistance data** on alternative module designs
- **Cell fracture strength** as a function of processing variables



Circuit designs

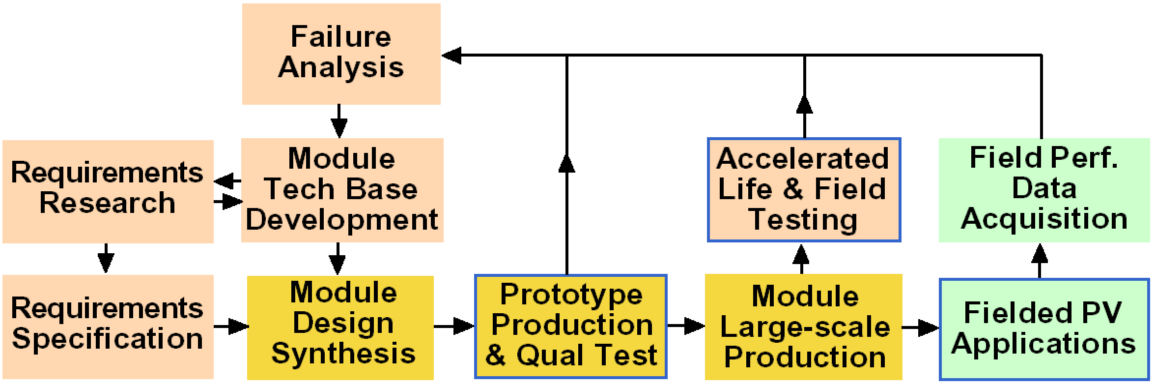


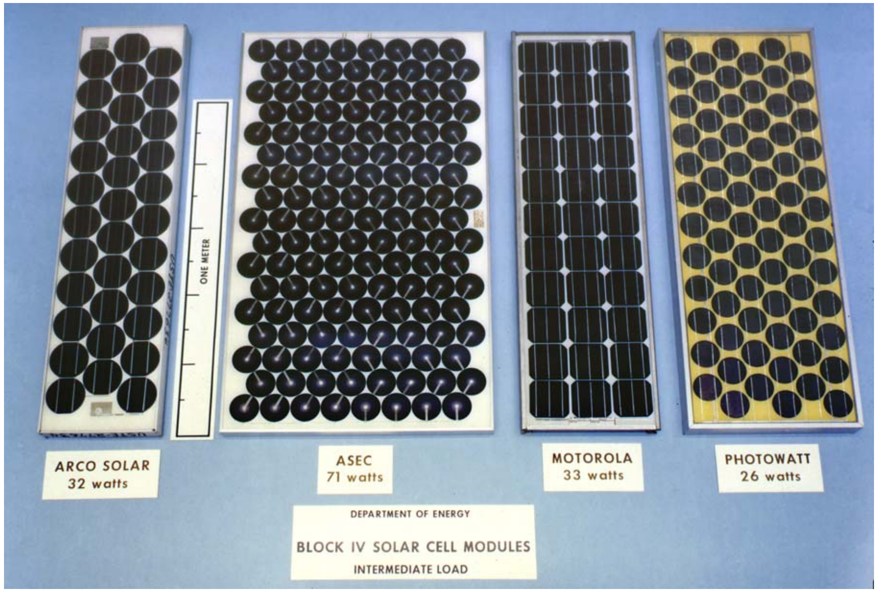
Fatigue strength



Cell strength

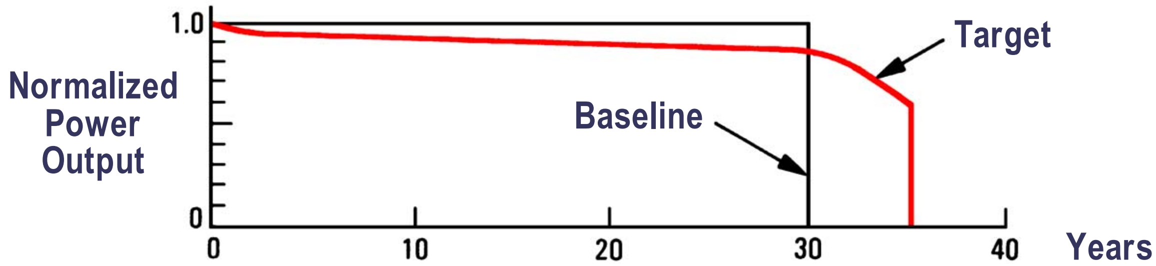
By 1980 (Block IV), Modules had Matured Substantially





- Glass superstrate design
- PVB & EVA encapsulant
- Rear surface films
- Aluminum frames
- Multiple cell interconnects
- Series/parallel cell strings
- Integral bypass diodes

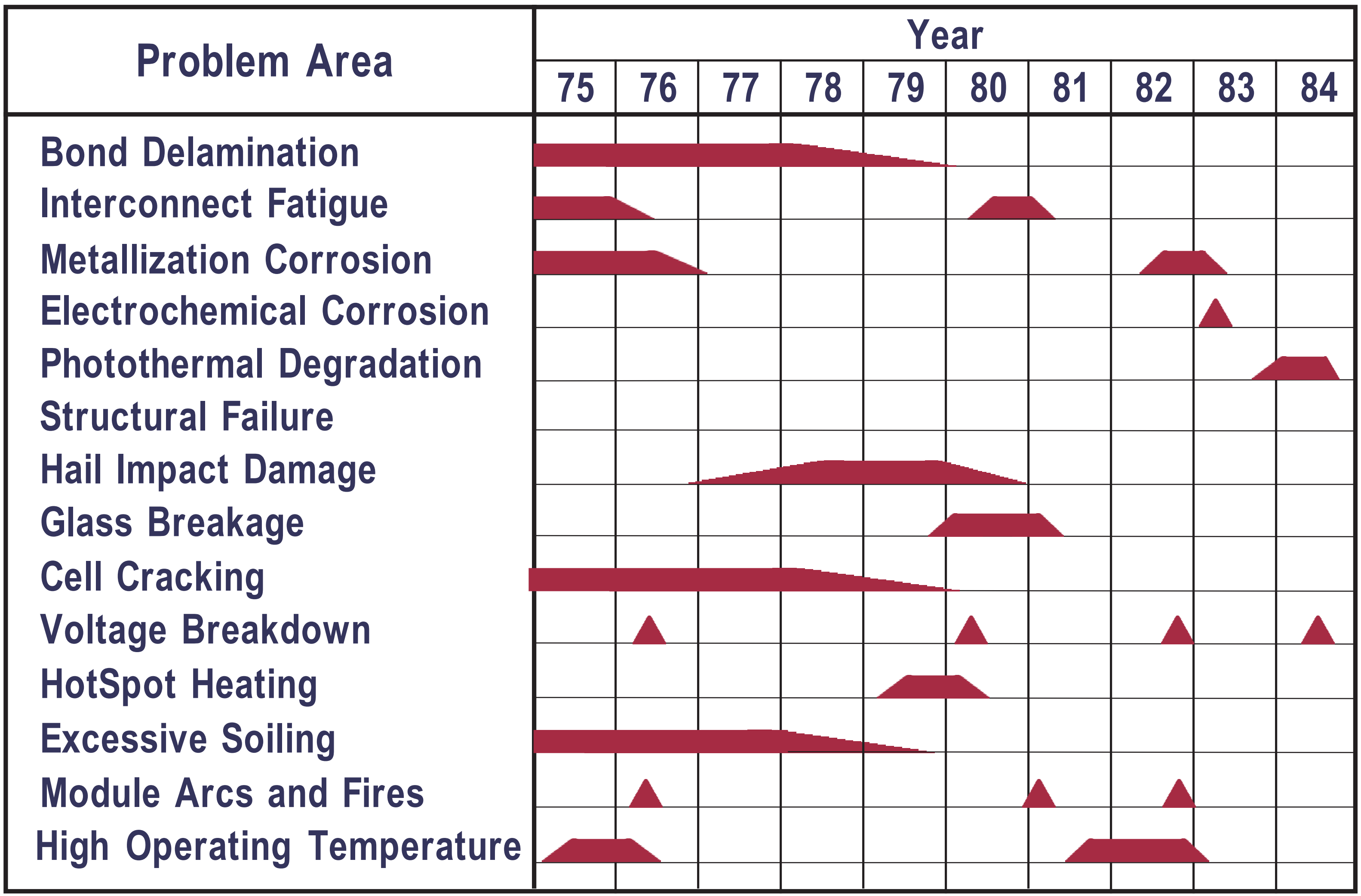
1980s Focus: Develop Technology Base for 30-year Life Low-Cost Modules



Type of Degradation	Failure Mechanism	Units of Degradation	Level for 10% Energy▲Cost Increase* k=0	k=10	Allocation for 30-year Life Module	Economic Penalty
Component failures	Open-circuit cracked cells	%/yr	0.08	0.13	0.005	Energy
	Short circuit cells	%/yr	0.24	0.40	0.050	Energy
	Interconnect open circuits	$\%/yr^2$	0.05	0.25	0.001	Energy
Power Degradation	Cell gradual power loss	%/yr	0.67	1.15	0.20	Energy
	Module optical degradation	%/yr	0.67	1.15	0.20	Energy
	Front surface soiling	%	10	10	3	Energy
Module failures	Module glass breakage	%/yr	0.33	1.18	0.1	O&M
	Module open circuits	%/yr	0.33	1.18	0.1	O&M
	Module hot-spot failures	%/yr	0.33	1.18	0.1	O&M
	Bypass diode failures	%/yr	0.70	2.40	0.05	O&M
	Module shorts to ground	$\%/yr^2$	0.022	0.122	0.01	O&M
	Module delamination	$\%/yr^2$	0.022	0.122	0.01	O&M
Life-limiting wearout	Encapsulant failure due to loss of stabilizers	years of life	27	20	35	End of life

* k=Discount rate

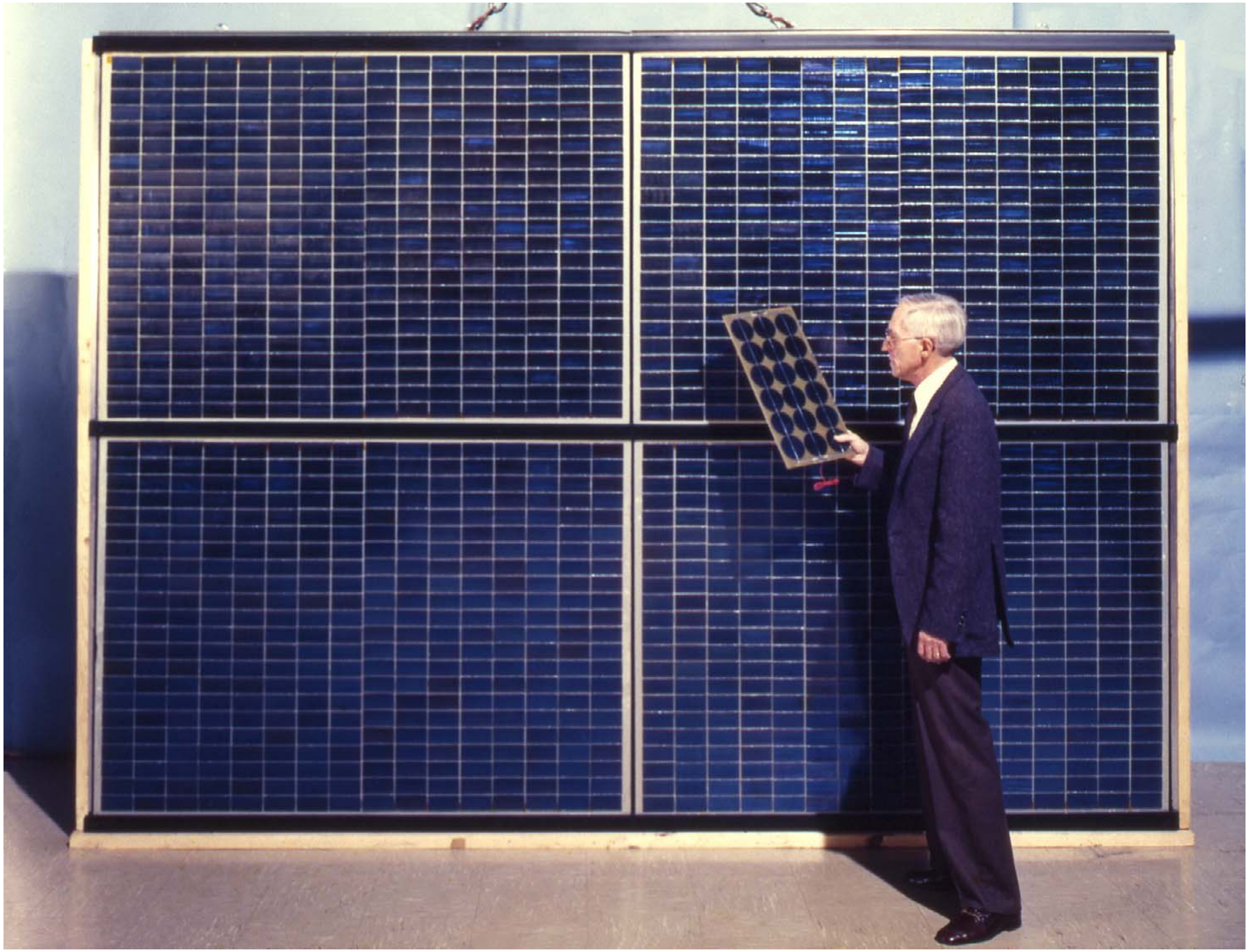
Evolution of Reliability Issues during FSA Project (1975-1985)



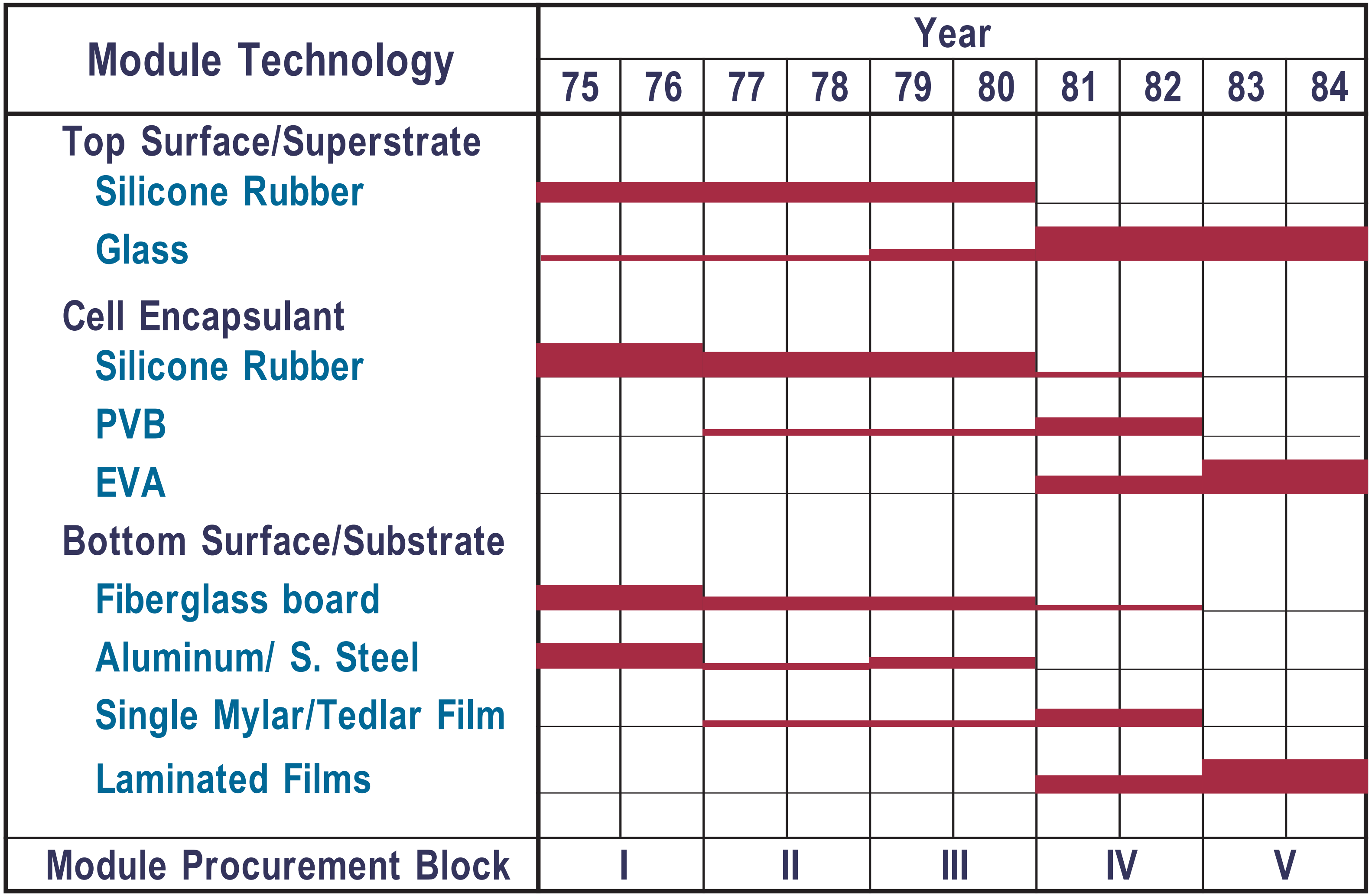
Evolution of Qualification Tests during FSA Project (1975-1985)

QUAL TEST	I	II	III	IV	V	NOTES
THERMAL CYCLING						
Range (°C)	-40 to +90	-40 to +90	→	→	→	
Number cycles	100	50	→	→	200	
HUMIDITY CYCLING						
Relative Humidity	90	→	→	→	85	
Temp. Range (°C)	+70*	-23 to +40	→	→	-40 to +85	*No cycling, 70°C
Number cycles	-	5	→	→	10	Constant for 168 h
MECHANICAL CYCLING*						*Excluding shingle modules
Pressure (kPa)	-	±2.4	→	→	→	
Number Cycles	-	100	→	10,000	→	
WIND RESISTANCE (kPa)	-	-	-	1.7*	→	*Shingles only
TWISTED MOUNT (mm/m)	-	20	→	→	→	
HAIL IMPACT						
Diameter (mm)	-	-	-	20	25.4	
Terminal Velocity (m/s)	-	-	-	20.1	23.2	
Num. Impacts	-	-	-	9	10	
HOT-SPOT HEATING (h)	-	-	-	-	100	
ELECTRICAL ISOLATION (volts)	-	1500	→	2000*	3000*	*1500 for resid. modules

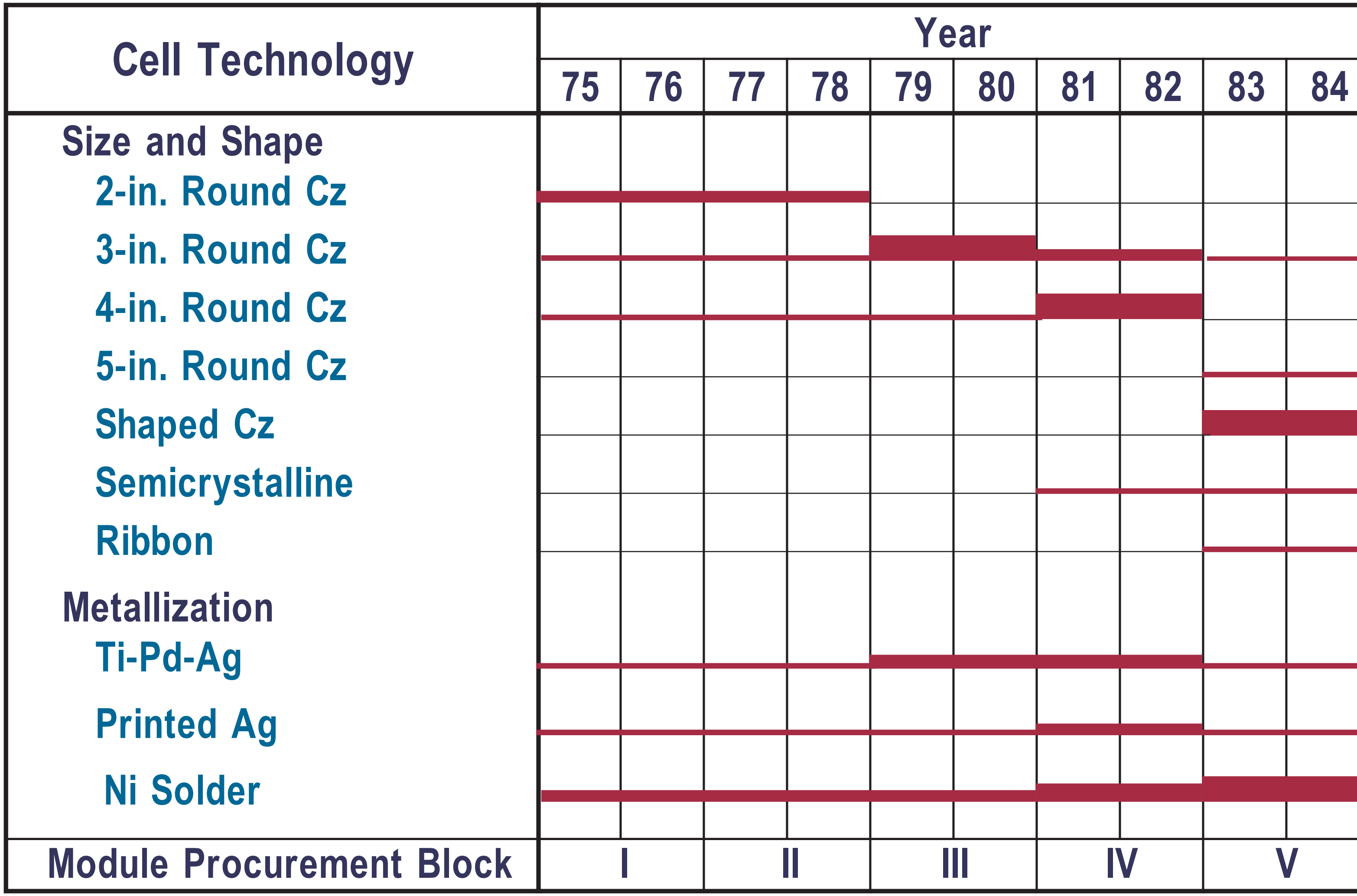
By 1984 we'd Completed the Block V Module Development Cycle



Evolution of Module Construction during Block Buys (1975-1984)



Evolution of Crystalline Si Cells during Block Buys (1975-1984)

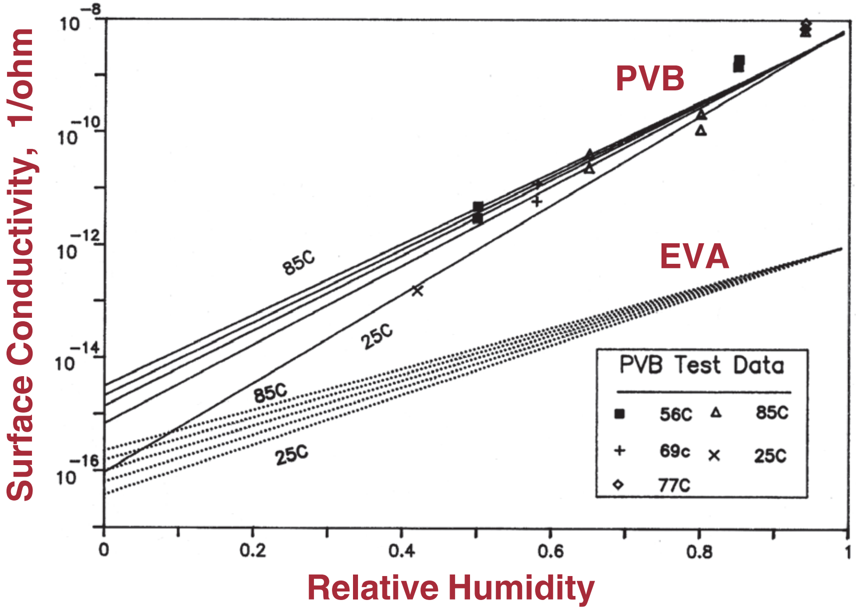


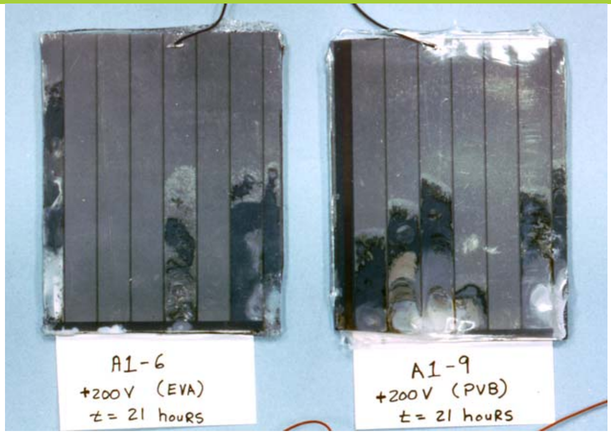
By the mid 1980s we'd Completed Some Big Full-Scale Systems

Late 1980s Focus: Develop Technology Base for Long Life and High Voltages

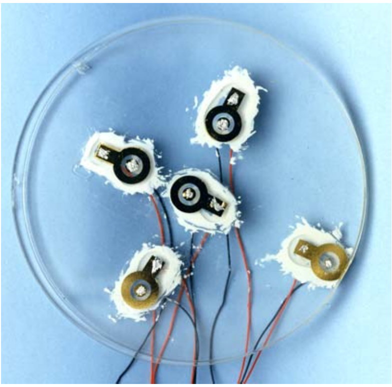
- **Bias-Humidity — Electrochemical Corrosion** driven by applied voltages and humidity
- **Voltage Breakdown and Arcing** through rear surface films and to frame
- **Long-term UV-Thermal Aging**

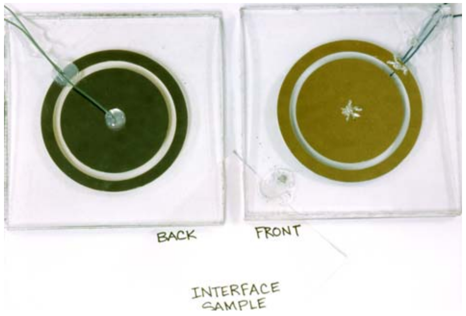
Late 1980s Focus #1: Electrochemical Corrosion Research



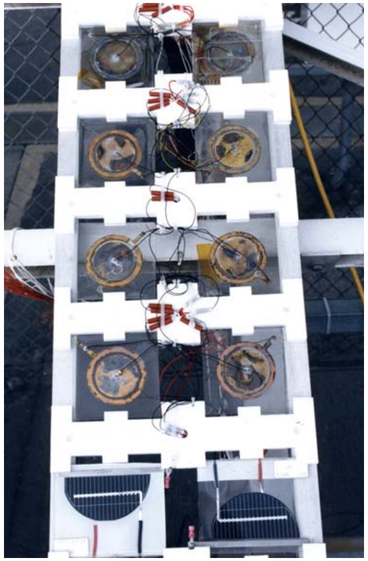


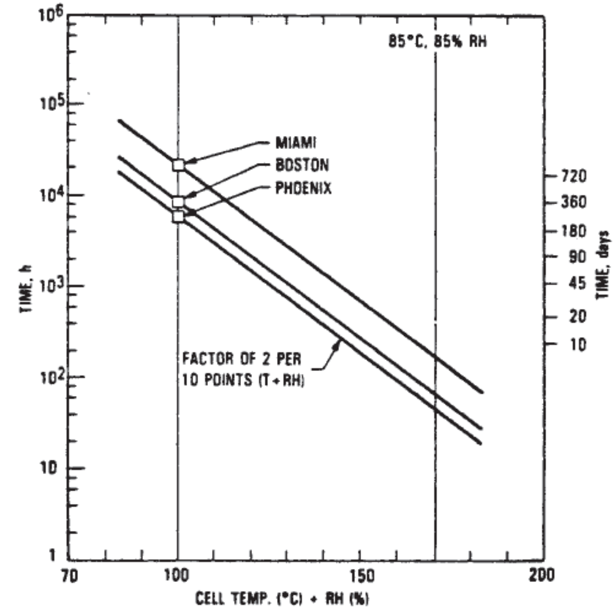
Accelerated Lab Testing





Fundamental Property Characterization

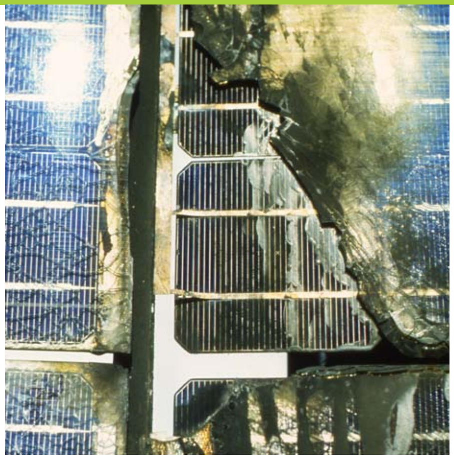




Correlation to Field Conditions

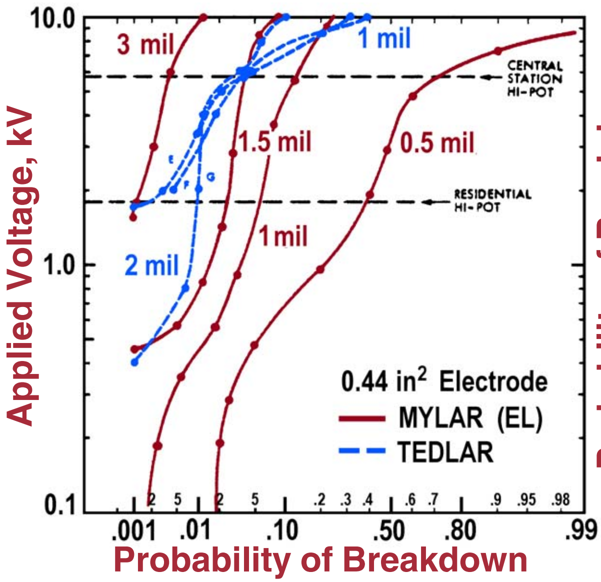
Late 1980s Focus #2: Voltage Breakdown & Insulation

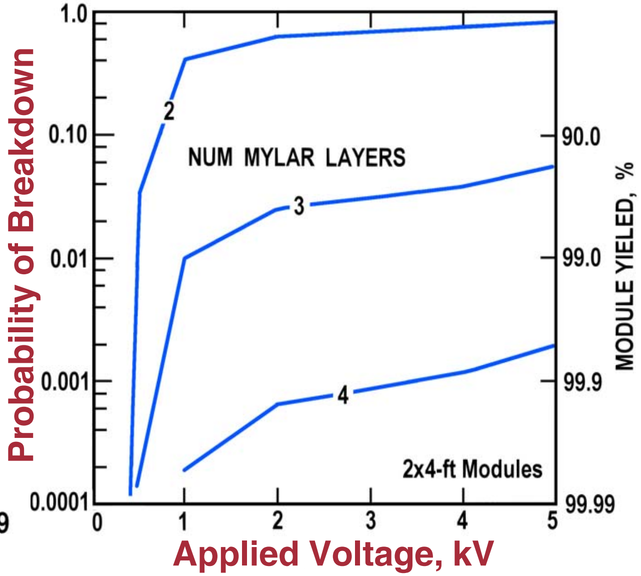
Module Frame Insulation Test

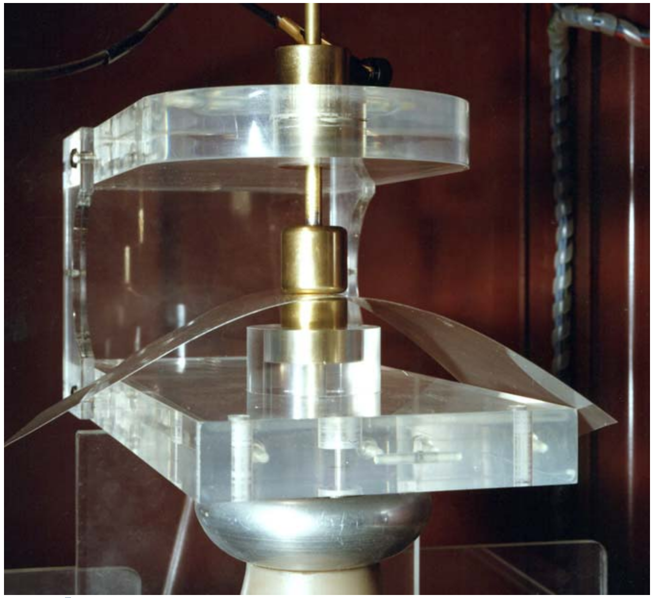


Field Failure

Biddel Partial Discharge Tester

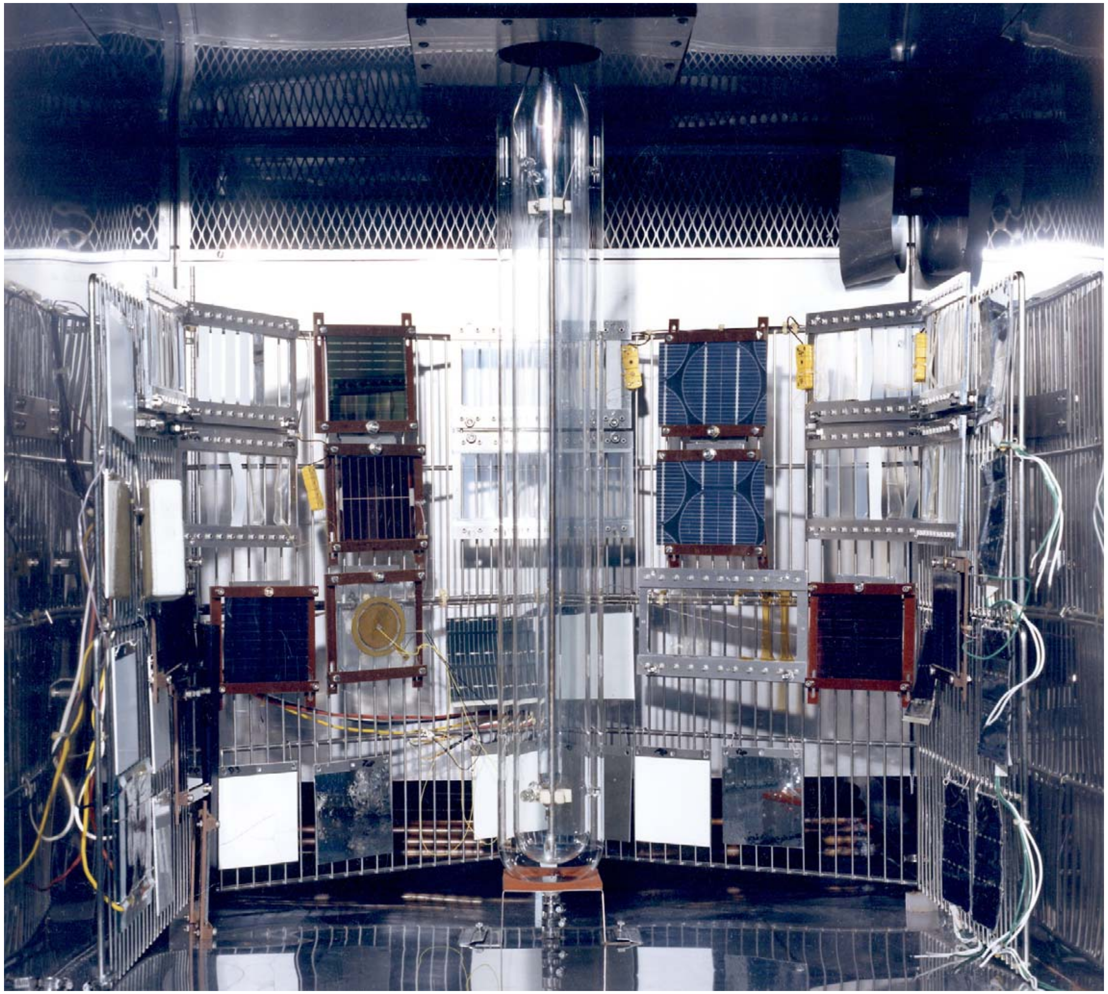




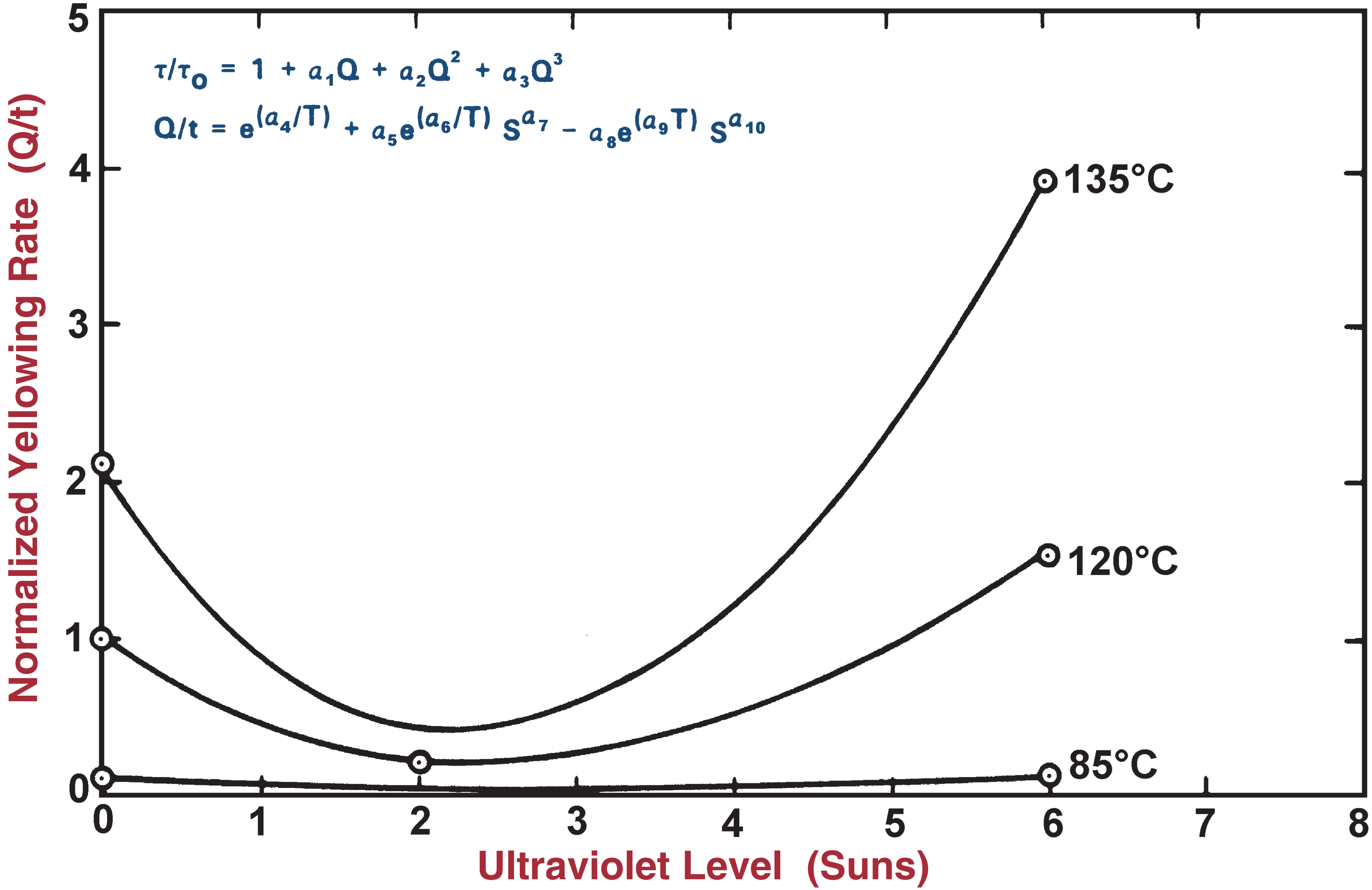


Fundamental Property Characterization

Late 1980s Focus #3: UV-Thermal-Humidity Aging



Transmission Loss through EVA vs Temperature and UV Level



Hourly Calculation of EVA Yellowing Rate in Phoenix

From curve-fit of parametric UV -Temp Yellowing data for EVA

Yellowing Rate at each Temperature-UV Level

Cell temperature, °C	UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	65	61	58	55	52	49	46	44	41	39	37	35
65	33	31	29	28	26	25	24	23	21	20	19	18
55	16	15	14	13	13	12	12	11	11	10	10	9
45	7	7	7	6	6	6	6	5	5	5	5	4
35	3	3	3	3	3	3	2	2	2	2	2	2
25	1	1	1	1	1	1	1	1	1	0.9	0.9	0.9
15	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
5	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1

From SOLMET hourly weather records for Phoenix

Annual Hours at each Temperature-UV Level

Cell temperature, °C	UV level in suns											
	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75	0.85	0.95	1.05	1.15
75	0	0	0	0	0	0	0	0	0	11	4	0
65	0	0	0	0	0	1	17	24	107	294	167	6
55	0	0	0	32	18	56	130	81	201	142	177	17
45	22	74	32	110	62	84	144	73	172	154	55	1
35	134	131	63	124	97	93	113	49	53	17	0	0
25	190	129	92	86	53	21	22	0	0	0	0	0
15	129	94	36	35	8	0	0	0	0	0	0	0
5	55	20	3	0	0	0	0	0	0	0	0	0

Conclusions from UV-Thermal-Humidity Aging

- **Predicted power loss after 30-years in Phoenix:**
  - Ground-mounted array = 3.5%
  - Roof-mounted array = 7.9%*

UV-THERMAL TESTING CONCLUSIONS

- UV response can be very nonlinear and difficult to accelerate
- Thermal response is much more predictable (typically Arrhenius with approx rate doubling each 10°C)
- Accurate regulation of temperature is critical to successful UV testing

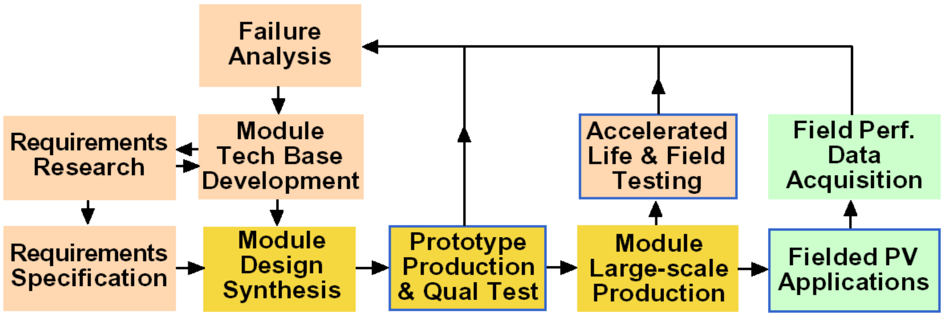
* Because roof array operates at higher temperature

By 1990 Many More Full-Scale PV Systems had been Completed



JPL Role in National PV Program Sunsetted in the Early 1990's

Summary Observations from 20 years developing PV



- **Overall closed-loop module development process worked quite effectively; Critical elements included:**
  - **Qual tests for quick production screening**
  - **Full-up systems tests for definitive operational feedback**
  - **Mechanism-level life testing for root-cause solution development**
- **Module Technology Base Development worked very well**
  - **Encapsulation systems development (EVA, primers, etc)**
  - **Requirements Development (natural environments, UL 1703, NEC 690)**
  - **Engineering Tech Base Development (fatigue, corrosion, glass strength, hail resistance, hot-spot heating, voltage breakdown, etc)**
  - **Failure analysis and measurement techniques**

Summary Observations (Con't)

- Rapid open communication between all parties worked very well
  - Rapid thorough feedback to all parties
  - Great teamwork across many organizations (Total JPL FSA project had 131 organizations under contract)
  - Engineering (ES&R, Module Proc, & Encapsulation Devel) had a total of 37 organizations under contract)
  - The dozens of reports and papers documenting the Engineering technologies developed are cataloged at:
    http://www2.jpl.nasa.gov/adv_tech/photovol/PV_pubs.htm

- This was one of the most rewarding and fun experiences of my life — a massive learning opportunity
  - Broad charter to address all obstacles
  - Robust budgets to support the effort
  - Great teamwork across many organizations